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Research paper



Fusion of Blockchain in The Digital Agriculture Food Supply Chain: A Comprehensive Review

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Abstract

Blockchain technology operates as a decentralized digital ledger, ensuring data integrity and enabling asset tracking. Its unique features offer potential improvements to conventional agri-food supply chains. Blockchain-based traceability solutions enhance producers' ability to monitor their goods while fostering consumer confidence in product origins and authenticity. However, current research lacks a comprehensive evaluation of both the advantages and limitations of Blockchain in the agri-food sector. This study addresses that gap by conducting a systematic review of 153 research papers published in the duration of 2016 to 2024, answering six key research questions. The analysis explores the benefits and challenges of Blockchain adoption, particularly from an industry perspective. Key findings highlight crucial research areas, including the need for specialized training for both stakeholders and businesses, the integration of complementary technologies such as Big Data and Edge Computing, and the development of practical tools to support developers.

Keywords: *Agriculture; Blockchain; Smart contracts; Transparency; Security; Food supply chain*

1. Introduction

This Blockchain technology is a subset of Distributed Ledger Technologies (DLTs) and facilitates transaction recording across a decentralized network of nodes. By leveraging cryptographic methods, it ensures that once data is recorded, it remains unaltered, enhancing both security and transparency. This makes Blockchain an effective tool for tracking assets and verifying information integrity [1]. In the agri-food sector, Blockchain has the potential to revolutionize food traceability by enabling end-to-end tracking throughout the supply chain. From production to consumer purchase, every stage can be securely documented, improving accountability and strengthening consumer trust in food authenticity [2]. This system not only enhances food safety and quality control but also benefits producers by increasing their visibility in the supply chain.

Additionally, Blockchain can be employed to establish digital identities for food products, incorporating key details such as origin, production processes, and certifications. This level of traceability empowers consumers to make well-informed purchasing decisions while promoting sustainable and ethical food production practices. By increasing transparency and security within the supply chain, Blockchain technology can foster greater consumer confidence in the food industry. Despite its potential, a thorough evaluation of Blockchain-based traceability systems is still missing in existing literature, particularly concerning technical implementation, as well as their advantages and limitations. To bridge this gap, this study conducts a literature review to assess the maturity of Blockchain applications in the agri-food domain. Six key research questions are formulated to examine the role of Blockchain in supporting supply chain operations from both consumer and stakeholder perspectives. The analysis is based on 153 selected studies, identified and filtered using the PRISMA framework [3]. This review also explores industry involvement in adopting decentralized architectures and examines relevant security considerations. Furthermore, the paper outlines potential research directions for industry adoption and Blockchain developers.

The structure of this paper is as follows: Section II introduces Blockchain technology, highlighting its benefits within the agri-food supply chain industry and presenting a common system architecture. Section III reviews some existing literature and based on that, it provides the review strategy used in this review. Section IV discusses the review carried out based on the research questions framed. Lastly, Section V concludes with a discussion on key insights and future opportunities.

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2. Background

2.1 Blockchain

Blockchain technology is characterized by its decentralized nature, with data distributed across multiple devices rather than being stored in a single centralized server. Unlike traditional systems, Blockchain and other Distributed Ledger Technologies (DLTs) operate independently of a central authority, allowing data to be shared and maintained collectively by all participants. Each participant in the network possesses a copy of the ledger, and any updates are synchronized across all copies, ensuring consistency and reliability. This decentralized approach enables Blockchain to function as a secure and trustworthy intermediary [4]. Once transactions are recorded on the Blockchain, they become permanent and immutable. These records are structured into blocks, and the computers responsible for processing Blockchain transactions are known as nodes.
The process of adding new blocks to the Blockchain, known as mining, involves solving complex cryptographic puzzles using hash functions. This computational process plays a crucial role in maintaining the integrity and security of the chain. To further enhance security, all shared data within the network is encrypted.

2.2 Application of blockchain in the agriculture food supply chain

The inherent features of Blockchain technology enable systems to be transparent and highly reliable. One of its key advantages is traceability, which is achieved through the immutability of recorded data. In the context of supply chains, traceability refers to the ability to reconstruct a product's journey from production to distribution [5]. This capability helps define the responsibilities of each participant in the supply chain, ensuring accountability and strengthening consumer confidence in food safety and quality. However, given the complexity and scale of supply chains, tracking products from raw materials to final consumers can be costly [6], necessitating an efficient and scalable solution. Such a system must be able to maintain consumer trust [7].
Blockchain technology provides a viable solution due to its unique characteristics: (i) it operates as a decentralized system, eliminating reliance on a single server that could create a point of failure, (ii) its immutability ensures that recorded data remains unchanged, making it easier to trace information while preventing tampering, and (iii) it can function as either a public or private system [8], [9], allowing it to be tailored to specific use cases while still ensuring transparency and fraud prevention.
Most proposed frameworks identify two primary participants: the end consumer and the producer. The producer role can extend to include farmers, distributors, and retailers, with each entity acting as a node within the decentralized network. Consumers can access immutable traceability data directly from their devices by scanning a QR code or using an RFID tag [10]. On the other hand, producers can input new data, which is managed by predefined smart contracts. These contracts play a critical role in verifying the authenticity of the data before it is added to the Blockchain. Additionally, data may also be collected from IoT sensors, processed by a central unit, and then recorded onto the Blockchain. The stored transactions can subsequently be uploaded to the InterPlanetary File System (IPFS) [11]. A widely accepted architecture summarizing various approaches to agri-food traceability through Blockchain technology is illustrated in Figure 1.

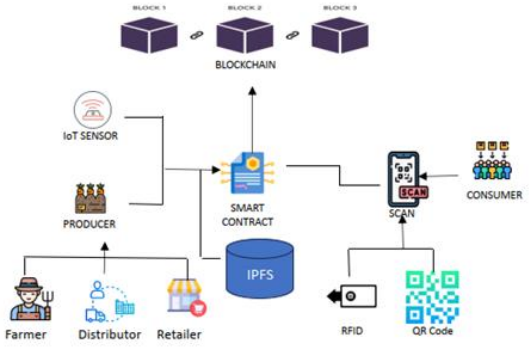


Fig. 1: Agri-food traceability through Blockchain.

The figure illustrates a comprehensive agri-food traceability framework leveraging Blockchain technology, IoT, and smart contracts to ensure transparency, security, and accountability across the food supply chain. The process begins with IoT sensors deployed at the production level, capturing real-time data related to environmental conditions, farming activities, or product handling. This data is then transmitted to a smart contract, which acts as an autonomous, self-executing protocol, ensuring that information is securely validated and stored. All validated data is logged onto the Blockchain ledger via multiple distributed nodes (Blocker 1, 2, and 3), ensuring immutability and decentralization. The system also integrates IPFS (InterPlanetary File System) for efficient, distributed data storage.
From the producer end, the data flows through key stakeholders—farmer, distributor, and retailer—with each transaction or movement being recorded in the blockchain. For end-user interaction, products are embedded with QR codes or RFID tags, which consumers can scan using their smartphones. This action retrieves the full traceability record—from origin to point-of-sale—offering transparency and fostering trust in the product's authenticity and safety. This blockchain-powered system thus strengthens traceability by creating an unalterable chain of data that all stakeholders, including consumers, can access and verify at any point in the agri-food supply chain.

3. Literature Review

Several literature reviews have explored Blockchain's role in supply chain management. Zhao et al. reviewed studies on Blockchain applications in supply chains up to 2019, covering manufacturing, water management, traceability, and security [1]. Niknejad et al. examined Blockchain in smart agriculture, emphasizing traceability and IoT sensors [12]. Other studies focus on Blockchain's integration with Industry 5.0 technologies, addressing food traceability, composition monitoring, and waste reduction [13]. Some reviews analyze cybersecurity concerns in Blockchain-based supply chains, while others assess technical implementations, noting limited real-world applications and cost-related challenges [14].

Taxonomy-based analyses have been conducted on Blockchain adoption models [15], with some studies focusing on sustainability in agri-food supply chains [16]. Research also highlights Blockchain's benefits, such as fraud prevention, decentralized structures, and improved quality control [17][18]. Additionally, studies examine adoption trends across different countries [19] and discuss Blockchain's early-stage development [20]. Another review applies a SWOT analysis to Blockchain adoption in supply chains, identifying benefits like anti-counterfeiting and increased trust while noting challenges such as industry standards and interoperability issues [21]. Our study differs by examining not only product traceability but also the broader impact of Blockchain on agri-food, security concerns, and the integration of additional technologies. We also assess industry participation and their willingness to adopt this technology, considering both advantages and limitations. This review covers literature from 2016 to 2024, aiming to help new researchers identify key areas in Blockchain-based agri-food traceability and explore future research directions.
To ensure a structured and systematic approach, this review on Blockchain in the agri-food Supply Chain was designed around six key research questions (RQs), addressing critical themes, trends, challenges, and security considerations. The review planning involved the following steps from 3.1 to 3.6.

3.1 Defining the Research Questions

The research questions were formulated using the PICOC framework to systematically investigate blockchain applications in agri-food supply chains:

- Population (P): Studies exploring blockchain applications in agri-food supply chains.
- Intervention (I): Blockchain-based solutions for traceability, transparency, and security.
- Comparison (C): Blockchain-based systems versus conventional supply chain management methods.
- Outcomes (O): Effectiveness in addressing stakeholder challenges, improving data accessibility, and ensuring security.
- Context (C): Implementation of blockchain in real-world agri-food supply chain environments.

The research questions guiding this review are:

- RQ1: What are the key research trends in blockchain for agri-food since 2016?
- RQ2: What main themes have been studied in blockchain and agriculture?
- RQ3: How can blockchain address stakeholder challenges in the agri-food supply chain?
- RQ4: What information can stakeholders access and integrate through blockchain?
- RQ5: What research gaps exist between blockchain's benefits and limitations?
- RQ6: How is security considered in blockchain applications, and to what extent?

3.2 Selecting Research Databases

To comprehensively capture relevant literature, a systematic search was conducted across three leading academic databases:
- IEEE Xplore – Covering blockchain innovations, smart contracts, and security applications.
- Scopus – Encompassing multidisciplinary research on agriculture, supply chain management, and blockchain integration.
- Science Direct – Providing access to peer-reviewed studies on blockchain applications in
- agri-food systems.

These databases were selected based on their extensive coverage of high-impact studies relevant to RQ1 (research trends) and RQ2 (main themes in blockchain and agriculture).

3.3 Developing a Search Strategy

To ensure comprehensive article extraction, the search strategy incorporated key terms aligned with the research questions: "Blockchain," "agri-food supply chain," "food traceability," "smart contracts," "supply chain transparency," "data integration," and "blockchain security." Boolean operators (AND, OR) were used to refine the search queries, ensuring a thorough examination of literature relevant to RQ3 (stakeholder challenges) and RQ4 (information access and integration).

3.4 Inclusion Criteria:

- Studies were included based on the following conditions to ensure relevance to RQ5 (research gaps in blockchain benefits and limitations) and RQ6 (security considerations in blockchain applications).
- Published between 2016 and 2024 in peer-reviewed journals (aligned with RQ1's focus on research trends).
- Focused on blockchain applications within agri-food supply chains, addressing traceability, security, and stakeholder collaboration.
- Provided quantitative or empirical findings on blockchain's effectiveness in the industry.
- Written in English to ensure accessibility and consistency across studies.

3.5 Exclusion Criteria:

The following studies were excluded to maintain methodological rigor:
- Review articles, editorials, and non-peer-reviewed studies.
- Studies unrelated to blockchain-based solutions in agri-food supply chains.
- Articles lacking empirical data on blockchain implementation, security, or stakeholder impact.

3.6 Performin1g Review

This step is divided and performed in the following two steps: 3.6.1 and 3.6.2

3.6.1 Primary Search: Identifying Relevant Studies

A structured search was conducted across three major databases, selected for their relevance to blockchain technology and supply chain management:

- IEEE Xplore – 94 records (blockchain innovations, smart contracts, security).
- Scopus – 79 records (blockchain applications in supply chains and agriculture).
- Science Direct – 84 records (peer-reviewed research on blockchain in agri-food systems).

This initial search yielded a total of 257 records. After removing 83 duplicates and out-of-scope records, the remaining 153 records were screened based on titles and abstracts to assess their relevance to the research questions:

- RQ1 (Research Trends in Blockchain for agri-food) → Studies covering blockchain developments from 2016 to 2024.
- RQ2 (Main Themes in Blockchain and Agriculture) → Studies categorizing blockchain applications in traceability, transparency, security, and efficiency.
- RQ3 (Stakeholder Challenges and Blockchain Solutions) → Studies discussing blockchain's role in improving trust, reducing fraud, and ensuring data integrity.

3.6.2 Secondary Search: Expanding Coverage

To strengthen the review's depth and rigor, a secondary search was conducted by:

- Reviewing the references of selected articles during the full-text review stage.
- Identifying additional relevant studies that aligned with RQ4 (Stakeholder Information Access & Integration) and RQ5 (Research Gaps Between Benefits & Limitations).
- Ensuring studies also addressed RQ6 (Security Considerations in Blockchain Applications), particularly regarding data protection, smart contracts, and encryption mechanisms.

To ensure transparency and reproducibility, the study selection process adhered strictly to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. This process was designed to systematically filter and assess the relevance of studies in alignment with the predefined research questions (RQ1–RQ6) and inclusion/exclusion criteria. A total of 153 studies met all criteria and were included in the final synthesis, forming the empirical foundation for analyzing:

- Blockchain trends and themes in the agri-food domain (RQ1, RQ2),
- Stakeholder-specific applications and challenges (RQ3, RQ4),
- Identified benefits vs. limitations and research gaps (RQ5),
- Blockchain security considerations across implementation contexts (RQ6).

This stepwise selection ensures methodological rigor, thematic coverage, and alignment with the review's objectives, as visualized in the PRISMA flow diagram (Figure 2) [22]. A PRISMA diagram (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) is a standardized flowchart used to transparently illustrate the selection process of studies included in a systematic review or meta-analysis. It helps readers understand how many records were identified through various sources (such as databases or manual searches), how many were screened, how many were excluded (and why), and how many were ultimately included in the qualitative and/or quantitative synthesis. The diagram is typically divided into four key phases: Identification, Screening, Eligibility, and Inclusion. In the Identification phase, all potential records are gathered. During Screening, duplicates are removed, and titles/abstracts are reviewed for relevance. In the Eligibility stage, full-text articles are assessed based on pre-defined inclusion/exclusion criteria. Finally, the included section lists the number of studies that meet all criteria and are included in the final analysis. The PRISMA diagram thus ensures transparency, reproducibility, and methodological rigor in literature reviews by clearly documenting each step of the study selection process. Following the screening process, 153 studies were selected. Data extraction and classification address the research questions, as summarized in Table 1. Table 2 gives a literature review idea in tabular form.

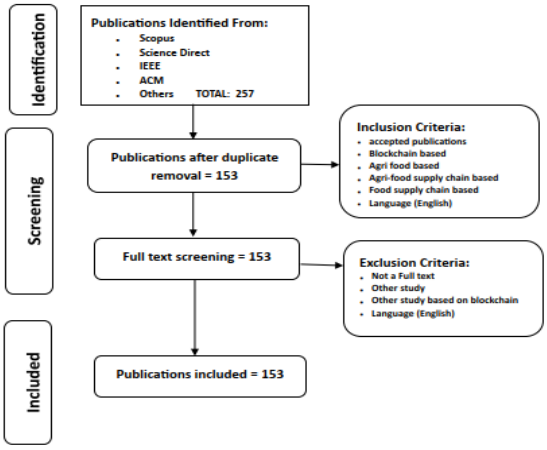


Fig.2: Research Methodology for Literature Review based on PRISMA

Table 1: Research questions and their answers

Data	Answer	RQ
Year of Publication	Since 2016	RQ1
Type of search	How is the topic analyzed?	RQ1
Area of Search	What type of analysis is performed?"	RQ2
Knowledge or software-based	Is the study focused on software or knowledge?	RQ2
Target problem solution	How is the target problem solved?	RQ3
Industries involvement	Is the industry involved?	RQ3
Information about the Product	What aspect of the product does the publication cover?	RQ4
Additional technologies	Which additional technologies were used?	RQ4
boundaries and benefits gap.	Are benefits greater than limitations?	RQ5
Traceability (Security) Topic	Is the Traceability analyzed?	RQ6

4. Results and Discussion

In this section, we show the main results obtained after the analysis of the selected papers. Results are categorized based on the RQs identified in Section 2. Table 2 shows the selected papers' details based on the research questions. This systematic review explores how blockchain is being used to help agri-food supply chains. To ensure accuracy and reliability, the study followed a clear, structured approach. paragraphs must be justified alignment. With justified alignment, both sides of the paragraph are straight.

Table 2: Literature Review details based on Research Questions

Research Question	References
RQ1	[9] [11] [12] [13] [22] [13] [22] [41] [42] [43] [44] [45] [47] [49] [50] [52] [58] [62] [70] [72] [90] [94] [100] [101] [106] [108] [110] [126] [141] [145] [151] [153] [[159]
RQ2	[10] [11] [12] [13] [14] [16] [18] [22] [25] [41] [42] [43] [44] [45] [46] [47] [48] [50] [51] [53] [54] [[55] [56] [57] [58] [59] [60] 61] [62] [63] [64] [65] [66] [67] [68] [69] [70] [71] [72] [[73] [74] [75] [76] [77] [78] [79] [80] [81] [82] [83] 84] [85] [86] [87] [88] [89] [91] [92] [[93] [94] [95] [96] [97] [98] [99] [100] [103] [104] [105] [106] [107] [109] [111] [112] [113] [114] [117] [118] [121] [125] [127] [129] [130] [131] [134] [135] [136] [138] [142] [149] [150] [152] [155] [169] [172] [174]
RQ3	[1] [5] [6] [7] [8] [10] [14] [15] [19] [20] [21] [23] [26] [30] [32] [33] [34] [35] [42] [49] [53] [55] [56] [63] [69] [73] [83] [86] [87] [91] [93] [95] [96] [103] [104] [107] 121] [123] [127] [129] [130] 131] [133] [135] 137] [138] [143] [148] [154] [158] [161] [162] [165] [171]
RQ4	[1] [5] [6] [7] [8] [10] [14] [15] [19] [20] [25] [27] [28] [29] [31] [34] [35] [36] [37] [38] [39] [40] [41] [43] [46] [48] [49] [50] [51] [52] [[54][55] [56] [57] [60] [61] [63] [66] [67] [68] 69] [71] [75] [80] [81] [82] [[84] [92] [93] [98] [105] [107] [111] [112] [114] [125] [133] [139] [147] [156] [164] [173]
RQ5	[12] [15] [16] [19] [24] [25] [[58] [64] [72] [74] [88] [90] [101] [102] [115] [116] [119] [124] [132] [144] [160] [167] [170]
RQ6	[5] [6] [8] [10] [15] [20] [26] [37] [38] [39] [44] [45] [48] [57] [61] [75] [76] [77] [78] [85] [89] [97] [99] [117] [118] [119] [128] [136] [137] [139] [140] [146] [157] [166] [168]

4.1 RQ1: Blockchain Research Trends in Agri-food Since 2016

Figure 3 shows a growing interest in Blockchain for agri-food, with research increasing over time. A slight decline between 2020 and 2021 may be due to the pandemic, but practical implementations began gaining traction from 2022 to address rising food demand [23]. Figure 4 categorizes the studies:

- 47% propose new solutions, but many remain unvalidated.
- 8% focus on implementations, though adoption is slow due to Blockchain's immaturity.
- 20% provide evaluative opinions, 10% focus on validation, and 15% are experimental, indicating ongoing practical assessments.

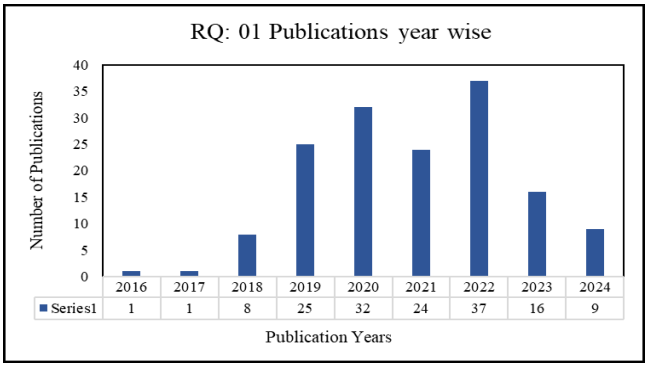


Fig. 3: Publication's distribution.

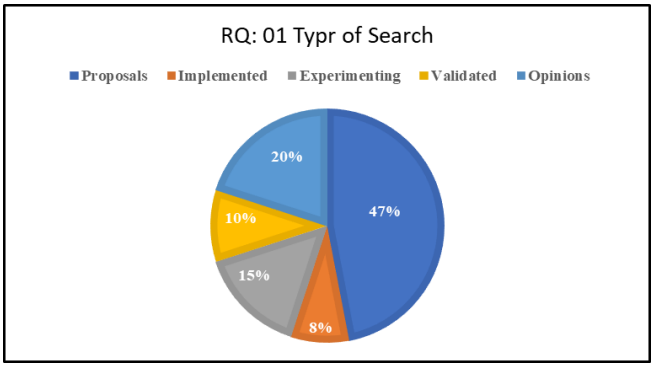


Fig. 4: Publication's distribution search type.

4.2 RQ2: Key Research Themes in Blockchain and Agriculture

Figure 5 shows the focus areas. Here, 57 papers cover technology, 37 discuss architecture, 13 papers represent business, 7 papers discuss quality, 16 papers discuss reliability, and 23 address performance. In addition to this, 78 software-based papers and 75 knowledge-based studies maintain a balance between technological development and theoretical advancements. Despite Blockchain's potential, several challenges affect real-world adoption [14]:

- Technical barriers: A gap exists between research and real-world application.
- Limited diffusion: Some sectors lack advanced traceability systems.
- Early-stage adoption: Investment risks hinder widespread use.
- Scalability issues: Expanding distributed networks can be complex.

Validating Blockchain solutions across all supply chain participants remains essential.

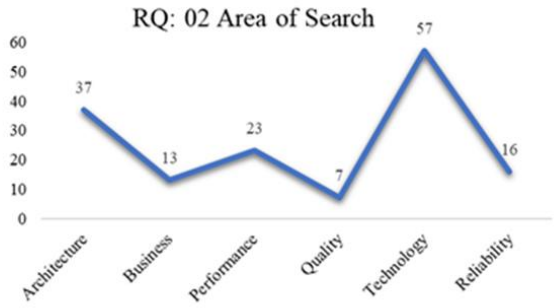


Fig. 5: Publication's distribution area of search.

4.3 RQ3: How Can Blockchain Address Stakeholder Challenges in Agri-food?

Blockchain enhances product identification, supply chain management, and traceability, as evidenced in 79 of the analyzed studies. It ensures end-to-end transparency by tracking agricultural products from production through distribution to retail. However, only four papers explicitly focus on interoperability—a critical but underexplored area. This limited attention is primarily due to the technical and organizational complexities involved in integrating Blockchain with legacy client-server architectures, enterprise resource planning (ERP) systems, and diverse IoT platforms. Unlike greenfield implementations, real-world supply chains often rely on heterogeneous IT infrastructures, which lack standard protocols for blockchain interoperability. Additionally, many current Blockchain solutions are designed in silos, without considering data formats, APIs, or governance models needed for seamless integration across systems and stakeholders.

The underrepresentation of interoperability in research has significant implications for adoption. Without interoperable solutions, stakeholders—especially SMEs and traditional agricultural operators—face high entry barriers, including data migration challenges, operational disruptions, and vendor lock-in risks. This discourages adoption and limits Blockchain's scalability across regions and sectors. Moreover, lack of interoperability hinders cross-border trade, real-time regulatory compliance, and data sharing across multiple supply chain actors. Transitioning to interoperable Blockchain systems also requires substantial investment in infrastructure, workforce training, and standards development—all of which remain underfunded and insufficiently coordinated.

Consequently, industry participation remains low, with 114 studies excluding direct industry involvement (only 8 involved actual industrial collaborators). This lack of engagement further slows down the development of practical, interoperable systems, as industries should ideally co-develop standards and lead quality assurance initiatives. While research interest in Blockchain peaked around 2018, a noticeable decline occurred post-2020, possibly due to the shift toward emerging technologies like AI or edge computing. Additionally, the absence of mature developer tools and integration frameworks continues to hinder real-world implementation of Blockchain-based traceability systems.

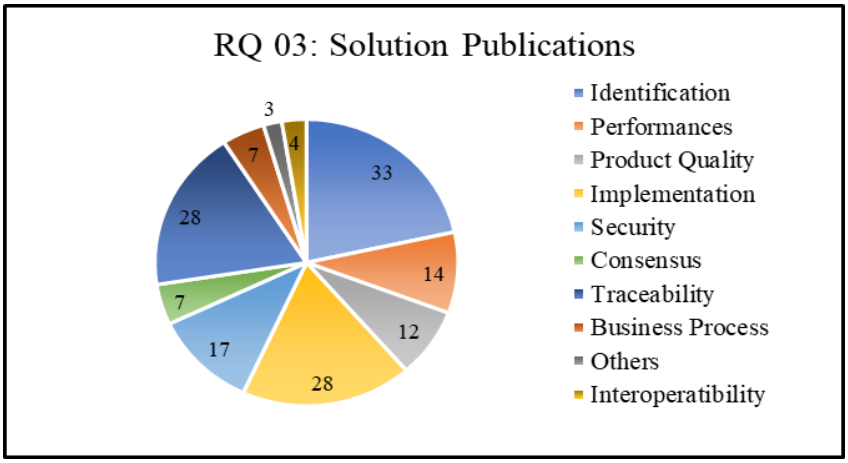


Fig. 6: Publication's distribution Solution.

4.4 RQ4: What Information Can Stakeholders Access Through Blockchain?

Blockchain optimizes agri-food traceability by recording a product's origin, transport, storage, and processing details (Figure 6). It also supports quality certification standards like HACCP, reducing counterfeiting risks and enhancing food safety.

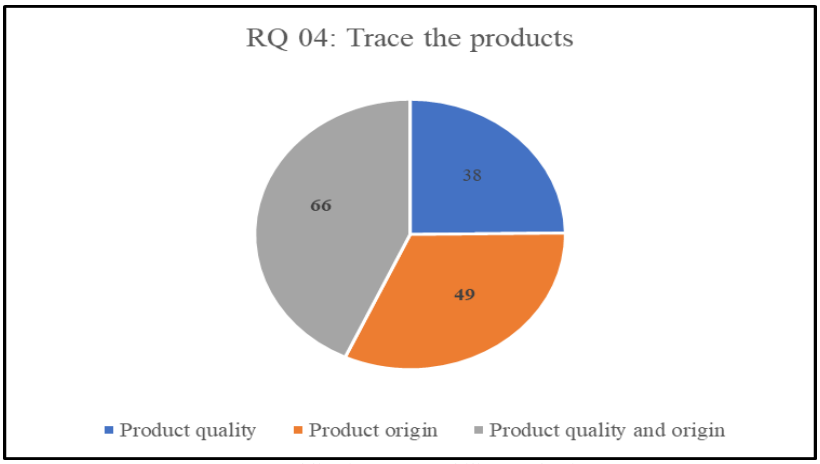


Fig. 7: Publication's Traceability mechanism.

The study also shows increased use of IoT and Big Data alongside Blockchain. IoT sensors help monitor factors like humidity, temperature, and transportation conditions. Edge computing further enhances data security and consumer interactions, making supply chains more efficient.

4.5 RQ5: What Are the Research Gaps Between Blockchain's Benefits and Limitations?

Studies highlight Blockchain's potential in agri-food supply chains but also its challenges, particularly in security and consensus mechanisms. Key benefits include product traceability, defect identification, and streamlined data management, all contributing to improved customer trust and operational efficiency. Additional advantages are:

- Supply chain enhancement
- Smart agriculture and predictive analytics
- Perishable food management
- Integration with existing technologies
- Crop monitoring via decision-support systems
- Regulations influencing stakeholder adoption

However, adoption barriers remain. Many stakeholders hesitate due to complexity, financial constraints, and regulatory uncertainty. Over 76% of studies lack real industry applications, highlighting a gap between research and practice. Additionally, the absence of user-friendly Blockchain tools, IoT integration, and initial investment support limits adoption. Shifting research focus from consumer trust to business confidence and practical tools could drive wider industry acceptance.

4.6 RQ6: How Is Security Addressed in Blockchain Applications?

Security in Blockchain-based traceability is gaining significant research attention. Among the 153 studies reviewed, 83 comprehensively address both data security and traceability, 37 focus specifically on infrastructure-level security, and 25 emphasize traceability assurance mechanisms. Only 8 studies fail to explicitly consider security aspects. Blockchain's inherent decentralization, immutability, and transparency naturally enhance fraud resistance and data integrity, especially when integrated with IoT in agri-food supply chains.

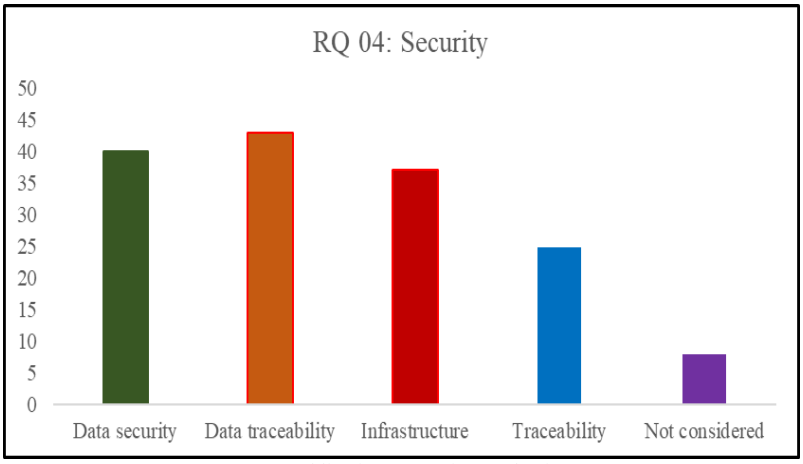


Fig. 8: Publication's security mechanism.

As IoT adoption continues to expand in agricultural environments—tracking environmental data, logistics, and product conditions—the demand for robust security architectures also grows. This is particularly important due to IoT's vulnerability to attacks such as spoofing, tampering, or data interception. Blockchain's ability to secure these data streams through distributed consensus and encrypted storage becomes essential.

Many studies, including Vangala et al. (2021) [77, 78], emphasize the use of cryptographic hash functions (e.g., SHA-256) to ensure data integrity. These hash functions generate unique, fixed-size outputs from input data, making tampering evident and enabling secure, verifiable records in the blockchain ledger. This is crucial in traceability applications, where even a minor alteration in supply chain records could lead to significant economic or public health consequences.

Digital signatures (based on public-private key cryptography) further enhance security by verifying the authenticity of transactions and participants (e.g., farmers, distributors). Elliptic Curve Cryptography (ECC) is increasingly adopted due to its strong security with lower computational overhead, making it suitable for resource-constrained IoT devices.

Consensus mechanisms such as Proof-of-Work (PoW), Proof-of-Stake (PoS), and Practical Byzantine Fault Tolerance (PBFT) play a central role in securing the blockchain network. While PoW offers strong resistance to tampering, it is energy-intensive and less suitable for agri-food systems with lightweight nodes. In contrast, PBFT and PoS are preferred in permissioned or consortium blockchains deployed in agricultural contexts due to their lower energy demands and faster finality.

However, several security vulnerabilities have been identified in this integration. For instance, smart contract exploits, such as reentrancy attacks, integer overflows, or logic errors, can compromise traceability systems if contracts are not rigorously tested or audited. Moreover, Sybil attacks and 51% attacks remain concerns in public blockchain implementations.

5. Conclusion

This paper reviews literature on Blockchain-based agri-food traceability, analyzing 153 studies from an initial pool of 257 references. The selection process ensures scientific validity through strict inclusion and exclusion criteria, offering a comprehensive overview of Blockchain's role in agri-food supply chains. Interest in this field has grown since 2016, shifting from theoretical proposals to practical implementations. While 55% of studies focus on technological aspects, 45% explore their application in food traceability. However, industry adoption remains limited, partly due to a lack of stakeholder involvement and disruptions caused by the pandemic.

Blockchain offers significant advantages across the supply chain: brands can enhance trust and sales, distributors benefit from transparent and tamper-proof supply chain management, and consumers gain product traceability through technologies like QR codes. The integration of IoT further strengthens traceability by enabling real-time access to detailed product information, including chemical composition and provenance, via smartphones. To promote wider adoption and bridge the gap between research and practice, this review recommends the following actionable strategies:

- Develop open-source, lightweight Blockchain toolkits tailored for small-scale farmers and cooperatives, enabling cost-effective adoption without requiring deep technical expertise.
- Establish industry-wide interoperability standards, as emphasized by Casino et al. (2021) [27], to facilitate seamless integration of Blockchain with existing ERP and supply chain systems, thereby reducing deployment complexity and vendor lock-in.
- Encourage the exploration and deployment of hybrid Blockchain architectures—combining public and private ledgers—to strike a balance between transparency and data privacy, particularly when handling sensitive production or trade data.
- Design capacity-building initiatives and training programs in collaboration with agricultural extension services and rural ICT centers to educate businesses and farmers on Blockchain's operational and economic benefits.
- Foster collaborative efforts between academia, industry, and government agencies to develop scalable frameworks integrating Blockchain with Big Data and Edge Computing, ensuring efficient real-time traceability across diverse agro-ecosystems.

These steps are critical not only for scaling Blockchain adoption in agri-food traceability but also for ensuring equitable participation, regulatory compliance, and long-term sustainability of digital agriculture systems.

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